

Direct mechanical mixing in a nanoelectromechanical diode

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We observe direct mechanical mixing in nanoelectromechanical transistors fabricated in semiconductor materials operating in the radio frequency band of $10 \sim 1000$ MHz. The device is made of a mechanically flexible pillar with a length of 240 nm and a diameter of 50 nm placed between two electrodes in an impedance matched coplanar wave guide. We find a nonlinear I - V characteristic, which enables radio frequency mixing of two electromagnetic signals via the nanomechanical transistor. Potential applications for this mixer are ultrasensitive displacement detection or signal processing in communication electronic circuits requiring high-throughput insulation.

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Mixing of electronic signals is essential for information processing [1]. A large number of electronic devices are used for signal mixing, all of which are based on a nonlinear I - V characteristic of one sort or another. Implementing a mechanical mixer is advantageous because of the higher throughput resistance, the insensitivity to electromagnetic shocks, and the discrete resonance structure of such a mechanical system. Conventional mechanical systems, however, have low resonance frequencies of only some kilohertz and are thus often not applicable for communication electronics. For these operating frequencies in the range of some tens of megahertz to several gigahertz are required. With the advent of nanoelectromechanical systems (NEMSs), the resonance frequencies of mechanical systems have now been pushed to several gigahertz simply by reducing the dimensions of the systems [2, 3]. Furthermore, we note that the integration of field emitting devices in NEMS is very promising for mechanically modulated millimeter wave sources. Key for functioning of these devices is an efficient mechanism for signal mixing, as will be demonstrated here.

In an earlier work, we have shown that a simple nanomechanical beam resonator driven into nonlinear response can be used for capacitive mechanical signal mixing [4]. In contrast to this, we now modulate the direct current through a nanopillar [5] by two radio frequency signals and show signal mixing over broad bandwidth. In Fig. 1, a typical nanoelectromechanical single electron transistor (NEMSET) or nanopillar is shown; the device is inserted between two electrodes forming source and drain contacts. The pillar is defined by electron beam lithography in silicon-on-insulator starting material, followed by thermal evaporation of 45 nm Au, and finally applying a reactive ion etch step to mill out the pillar (with CF_4). The oxide thickness was 390 nm and the crystalline Si top layer thickness was 190 nm.

For the measurements, we employ a standard dc technique to trace at first the current versus frequency response of the system, as shown in Fig. 2. We use an Ithaco (1210) current preamplifier in conjunction with an

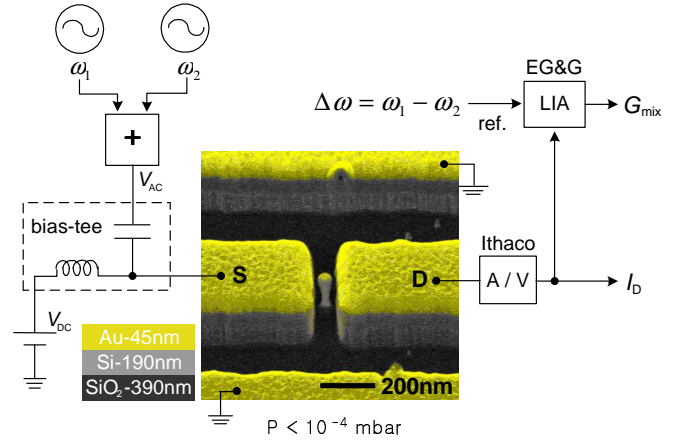


FIG. 1: Schematic of the measurement circuit with a bias tee, allowing a combination of ac and dc signals (V_{ac} and V_{dc}) for tracing the direct current (I_D at drain D) frequency dependence. Two synthesizers (ω_1 and ω_2) are used for direct mechanical mixing with the difference frequency $\Delta\omega$ as a reference for the lock-in amplifier. The nanopillar between the source and drain contacts is dry etched from a silicon-on-insulator material and covered with a gold top layer of 40 nm thickness (see scanning electron microscope graph).

EG&G lock-in (119). The bandwidth of the preamplifier is of the order of 20 kHz, thus ensuring amplification of mixing frequencies below this cutoff. The frequency dependent mixing signal can then be directly traced with the lock-in. The bias tee on the source side of the circuit is a standard Hewlett-Packard 33150A. The direct current through the device clearly gives a diodelike response, which depends on the mechanical response of the system. The nanopillar itself is set into motion by applying the ac signal leading to resonant Coulomb force (RCF) excitation at its eigenfrequencies, as we discussed elsewhere before [6, 7, 8].

We find four broad resonances-with the probe station (Desert Cryogenics TTP4) pumped to 10^{-4} mbar-of the

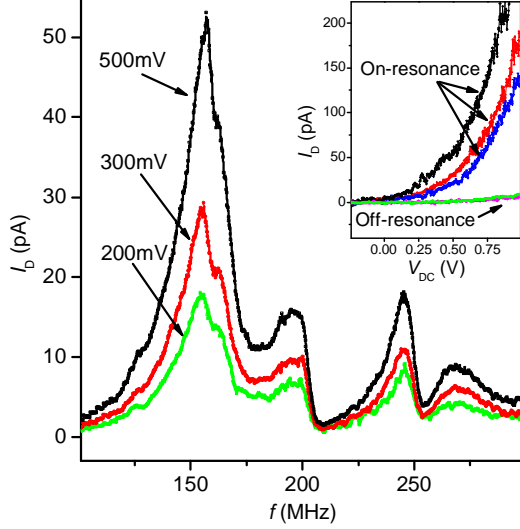


FIG. 2: Frequency spectrum of the direct current vs applied radio frequency. All measurements are performed at room temperature and 10^{-4} mbar helium gas pressure. The different traces correspond to enhanced dc bias voltages, as indicated. Inset: characterization of the nonlinear response of the nanopillar compared to off-resonance current at fixed rf signal.

nanopillar covering the frequency range from 100 to 300 MHz (see Fig. 2). The three different traces correspond to the three dc bias voltages from 200, 300, and finally 500 mV. The width of the resonances can be tuned by the nanopillar dimensions. We have chosen broader resonances in order to achieve mixing of a larger frequency range. The mechanical and electrical responses are typically modeled by commercially available program packages [9].

All measurements are performed at room temperature in vacuum under ($P < 10^{-4}$ mbar). The inset shows the full bias dependence of the current for on- and off-resonance positions; i.e., the ac excitation is fixed at 157, 196, and 245 MHz at a power level $P=16$ dBm. In other words, the difference between the electron current on and off resonances at $V_{\text{bias}} \sim 1$ V is more than two orders of magnitude. This is important since it indicates an excellent signal-to-noise ratio. Even more important is the highly nonlinear I - V characteristic, which is the necessary precondition for signal mixing or gain when operated as a nanomechanical transistor.

It has to be noted that the total current through such nanopillars is a combination of an ordinary tunneling current and a field emission current; it was outlined elsewhere [6, 7]. This effect was shown for the lateral as well as for the vertical (nanopillar) NEMSETs. Basically, field emission enhances conventional electron tunneling and leads to a higher emission current. In addition, the

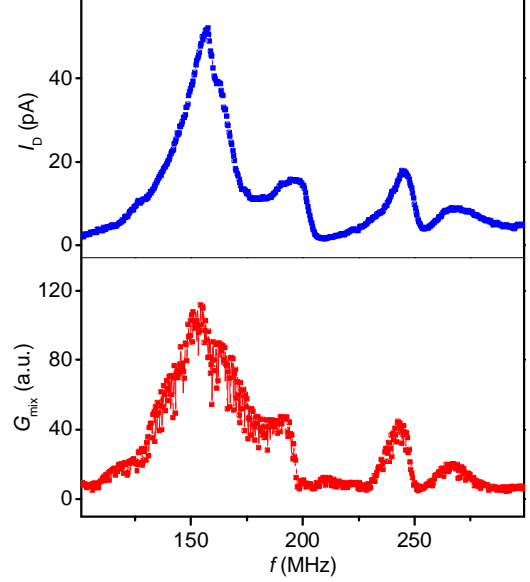


FIG. 3: Drain current I_D vs driving radio frequency signal under a dc bias of 500 mV (Top). Mixing signal dI/dV of the nanopillar excited by two synthesizers running at frequencies of ω_1 and $\omega_2/2\pi = \omega_1/2\pi + 731$ Hz (Bottom).

fact that electrons are shuttled by an island alters the classical Fowler-Nordheim plot [8]. This has the advantage that field emission can be regulated by changing the island dimensions. In addition, studying field emission through nanopillars has the potential to reveal the intricacies of field emission since the electron flow rate can be controlled precisely.

In order to make use of the nonlinear I - V characteristic for signal mixing, two synthesizers [9] (Agilent E8257D and HP 8656B) are applied, as shown in the circuit diagram of Fig. 1(a). The two synthesizers are phase locked and their output signals are combined [$V_{ac}(f1) + V_{ac}(f2)$] in an adder and sent to the sample. The difference frequency denoted by $\delta\omega = 2\pi\delta f = |f1 - f2|$ is used as a reference. This reference frequency is sent to the lock-in amplifier and is varied from 100 Hz to 2.6 kHz, where the bandwidth is limited by the current preamplifier and the lock-in stage. The final current is amplified as in the standard setup; for readout of the mixed signal, the direct current is further amplified by lock-in amplifier operating at the reference δf . The resulting measurements are shown in Fig. 3; here, we compare the direct current I_{dc} with the mixing signal G_{mix} in a frequency sweep. The mixing signal is proportional to the second derivative of the current as

$$G_{\text{mix}} \propto V_{ac1} V_{ac2} \frac{d^2 I}{dV^2}. \quad (1)$$

As can be seen, the resonance shape is maintained, as one would expect, which underlines the operation of the

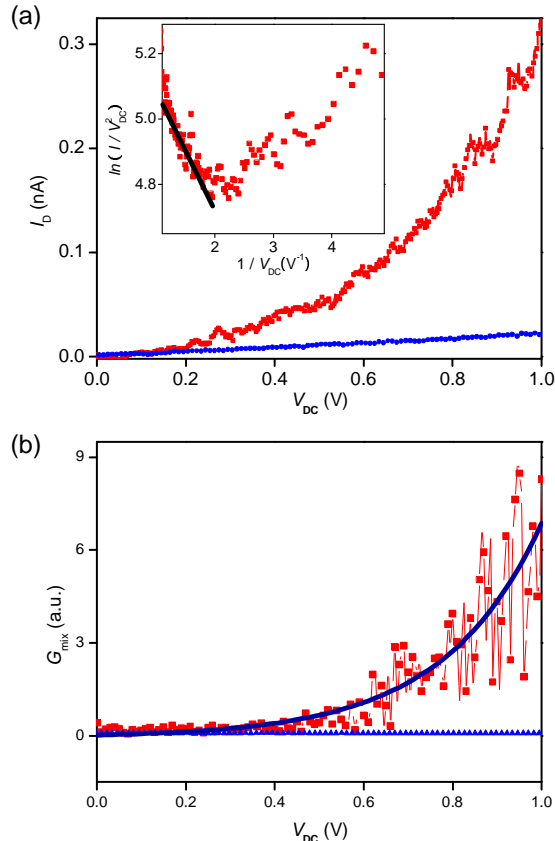


FIG. 4: (a) Bias dependence of the direct current through the nanopillar and the rf driver frequencies of 157 MHz on (red) and 210 MHz off resonances (blue). (b) corresponds to the mixing signal G_{mix} [on (red) and off (blue)]. Inset: Fowler-Nordheim plot with the solid line indicating a fit at high bias. At lower bias conventional tunneling is dominant.

nanopillar as a mechanical mixing element over a broad frequency range. We denoted the mixed signal as an effective conductance dI/dV with arbitrary units.

In Fig. 4, we compare the dc bias-dependence direct current and the mixing signal at a specific frequency (157 MHz). In Fig. 4(a), the current is shown on (red) and off resonances (blue); the response for the on-resonance trace follows the modified Fowler-Nordheim relation, we found earlier [10], while that of the off-resonance trace defines the background of tunneling electrons from source to drain. It has to be stressed that the difference between the on and off signals defines an excellent signal-to-noise ratio for this single electron switch operating at radio frequencies. Per cycle of mechanical motion of the nanopillar, it shuttles on average $\langle n \rangle = \langle I \rangle / ef$ electrons, where e is the elementary charge. For a current of 50 pA

at the resonance of 150 MHz, shown in Fig. 2, we obtain an average number of electrons of $\sim 10^3$ electrons.

The mixing signal is presented in Fig. 4(b) for the on- and the off-resonance cases. Again we find a stark contrast between both traces. The inset in Fig. 4 shows the standard Fowler-Nordheim plot. Similar to the dc results [10], we find for large bias voltages a linear dependence. The solid line indicates a fit according to Fowler and Nordheim, while for lower bias voltages, electron tunneling is dominant. In summary, we have demonstrated mechanical mixing in a silicon nanopillar that oscillates mechanically between two electrodes. This will have great impact for applications such as signal processing applications and sensor electronics. We also foresee that mechanical mixing will be extremely important for improving measurement sensitivity of NEMS, i.e., regarding quantum limited displacement detection, for self-excitation of NEMS and for noise measurements on electron shuttles [11].

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